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TNO report

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A tactile torso display improves orientation awareness in microgravity: a case study in the ISS.

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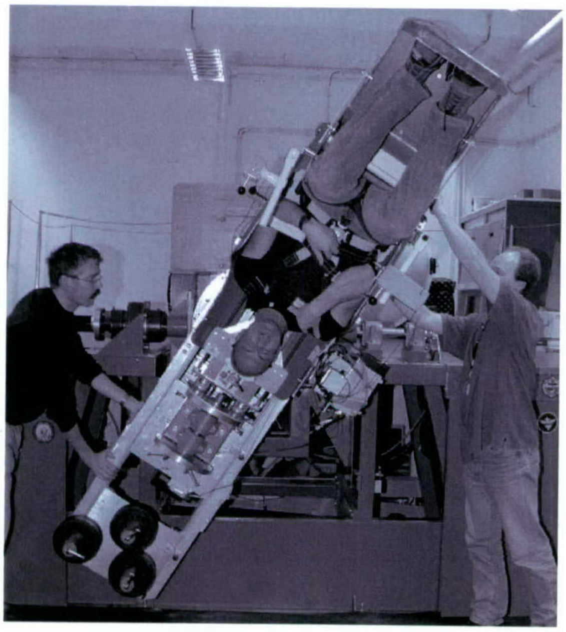
A tactile torso display improves orientation awareness in microgravity: a case study in the ISS.

In april 2004 is de Nederlandse astronaut André Kuipers afgereisd naar het Internationale Ruimtestation. Gedurende zijn verblijf in gewichtsloosheid heeft hij een aantal experimenten uitgevoerd, waaronder een aantal van TNO. Eén van de experimenten was met het TNO trilvest, een hulpmiddel dat astronauten helpt bij het ruimtelijk oriënteren.



Probleemstelling

Voor het comfort, de prestatie, en de veiligheid van de astronauten en kosmonauten in het Internationale Ruimtestation ISS moeten ze weten hoe ze georiënteerd zijn, zeker in kritische situaties zoals tijdens ruimtewandelingen of noodevacuaties. In het ISS ontbreken echter belangrijke visuele cues over wat onder en boven is, en in een gewichtsloze omgeving kunnen de otolieten, een onderdeel van het vestibulair systeem, evenmin onder en boven onderscheiden. TNO Defensie en Veiligheid, locatie Soesterberg heeft in opdracht van de Raad van Bestuur TNO en de Koninklijke Luchtmacht en samen met Dutch Space (in opdracht van de ESA) TOAST ontwikkeld: een Tactile Orientation Awareness Support Tool. Door op een specifieke locatie op de torso een trilsignaal te geven wijst TOAST de astronaut waar beneden is.

Beschrijving van de werkzaamheden

Een ESA-astronaut heeft een aantal experimenten uitgevoerd tijdens een 10-daagse missie naar het ISS. Om de effecten van TOAST in een microgravity-omgeving te onderzoeken is een speciale takenbatterij ontwikkeld waarmee objectieve prestatie en subjectieve beoordeling gemeten konden worden.

A tactile torso display improves orientation awareness in microgravity: a case study in the ISS.

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Resultaten en conclusies

De resultaten laten zien dat TOAST het voor de astronaut (onder de niet-dagelijkse omstandigheden van het experiment) beter, sneller en makkelijker maakt om zich te oriënteren, zowel met de ogen open als met de ogen dicht.

Toepasbaarheid

Naast astronauten kan deze technologie ook toegepast worden bij bijvoorbeeld vliegers, duikers en mensen met een vestibulaire stoornis.

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Samenvatting

Probleemstelling
Astronauten die in gewichtsloosheid zoals in het Internationale Ruimtestation ISS werken missen belangrijke informatie van hun evenwichtsorgaan en hun tastzin om zich te oriënteren. Met name in uitdagende situaties zoals bij een noodevacuatie of het verrichten van werkzaamheden buiten het station kan een oriëntatieondersteuningsmiddel belangrijk zijn. Deze studie onderzoekt of het oriëntatiebewustzijn van astronauten verbeterd kan worden door een trilsignaal op de torso te geven dat in de richting van 'beneden' wijst.

Werkwijze
In een gecontroleerd experiment in het internationale ruimtestation is een Tactile Orientation Awareness Support Tool (TOAST) getest. Tijdens het experiment voerde een astronaut een aantal orientatietesten uit in verschillende sensorische condities, bijvoorbeeld met zijn ogen open en dicht.

Resultaten
De belangrijkste resultaten laten zien dat TOAST het oriëntatiebewustzijn vergroot. De taken werden sneller, beter en met minder moeite uitgevoerd, zelfs als er ook visuele informatie beschikbaar was.

Conclusies en aanbevelingen
Deze casestudie bevestigt de potentie van het principe om oriëntatie informatie via de tastzin aan te bieden. Dit concept kan bijvoorbeeld worden toegepast bij astronauten, duikers, piloten en mensen met een vestibulaire stoornis

Summary

Purpose
Maintaining a good sense of one's orientation in a microgravity environment such as the International Space Station (ISS) is difficult because information from the vestibular and the proprioceptive system is lacking. Especially in challenging situations such as Extra Vehicular Activity and emergency evacuations an orientation support tool may be of critical importance. This study investigates if astronaut's orientation awareness can be improved by providing a vibration on the torso that indicates the direction of 'down'.

Methods
In a controlled experiment onboard the ISS, a Tactile Orientation Awareness Support Tool (TOAST) was tested. During the experiment, an ESA astronaut performed orientation tasks in different sensory conditions, such as with his eyes open and closed.

Results
The main results showed that TOAST improves orientation performance. Task completion was faster, better, and easier with TOAST support, even so when visual cues were available.

Conclusions and recommendations
This case study confirmed the potential of providing orientation information by the sense of touch, a concept that can, for instance, be applied for astronauts, divers, pilots and people with a vestibular dysfunction.

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A ESA Reference documents for the experiment

1 Introduction

In everyday life, we gather information about the world around us via different sensory systems, including our sense of touch. When the information that comes through one of our senses is degraded, for example when wearing protective earphones, our performance and comfort will be negatively affected. In a micro-gravity environment such as the International Space Station (ISS), astronauts completely lack specific sensory information. Especially the vestibular and cutaneous senses are affected. For example, there is no continuous pressure on the sole of the feet, there is no G-force that pulls clothing to the skin, and no gravitational acceleration to which the otoliths respond (in microgravity, the otoliths are effectively unloaded and cannot provide information about static head orientation). This sensory deprivation has several consequences for astronauts. Amongst other things, it affects the way they must perceive their subjective vertical. In Earth's 1G environment, we normally use four cues to determine the subjective vertical: visual cues, vestibular cues, proprioceptive cues and our ideotropic vector (i.e., we are inclined to see our own body axis as vertical; Graybiel & Kellogg, 1967). In a microgravity environment, vestibular and proprioceptive cues on what is up are absent (Benson, Guedry, Parker & Reschke, 1997; Glasauer & Mittelstaedt, 1998; Israel & Berthoz, 1989; Mittelstaedt & Glasauer, 1993; Reschke, Bloomberg, Harm, Paloski, Layne & McDonald, 1998). Then again, in a 1G environment we can maintain a correct spatial orientation even in situations in which not every sensory system provides information (Bles, 1981) so the lack of vestibular and proprioceptive cues does not necessarily degrade orientation performance.
One of the findings of studies done in weightlessness is that it enhances the magnitude of visual effects on inducing apparent self-motion (Young & Shelhamer, 1990; Young et al., 1993). Indications for an increased weight of visual cues in maintaining balance directly after flight was found by Bles and Van Raaij (1988) in their tilting room.

Data indicate that during the adaptation phase in the ISS, astronauts predominantly use visual cues from the station and colleagues to orient themselves. There are large individual differences though, both with respect to the time scale of this adaptation and the extent to which orientation illusions are experienced (Lackner & DiZio, 1993, 1997; Oman, 1988). During this adaptation phase, the unexpected visual cues of colleagues (e.g., colleagues oriented 'upside-down') can be very disturbing. The same holds for entering a different ISS module in an unexpected orientation due to the unfamiliarity with the station or due to sub-threshold rotation in the nodes between modules. Besides comfort, degraded orientation awareness may reduce performance of the astronaut. In this paper, orientation awareness is defined as knowledge about one's orientation in terms of pitch, heading and roll with respect to a certain frame of reference. Anecdotal evidence indicates that astronauts who visit the ISS don't recognise a module during the first days of their visit when they enter in a new orientation. In general, providing additional cues to astronauts to improve their orientation awareness may be expected to improve their performance and their well-being. This is especially relevant during short space missions.

In 2002, the Netherlands ministries of Education, Culture and Science and of Economic Affairs decided to support a 'visiting scientist' mission of Dutch ESA astronaut André Kuipers to the International Space Station. Shortly after, TNO Human Factors was invited to participate in the mission with a technology demonstration of its Tactile

Orientation Awareness Support Tool or TOAST[1]. TNO Human Factors has extensive experience in designing and testing tactile torso displays. These displays consist of numerous vibrating elements in a matrix form that covers the whole torso. A vibration at a specific location is the information carrier of those displays. Since a vibration on the torso is immediately mapped to the body co-ordinates (Van Erp, 2005), these displays may be powerful in presenting spatial information. Like the proverbial tap-on-the-shoulder directs your attention to the tapping person. This tap-on-the-shoulder concept (Van Erp & Verschoor, 2004) has proven its value in several orientation and navigation tasks, including course control in high speed boats (Dobbins & Samways, 2002), altitude control in helicopters (Van Erp, Veltman & Van Veen, 2003), road vehicle navigation support (Van Erp & Van Veen, 2004), as counter measure to spatial disorientation in aircraft (Van Erp et al., 2005) and as sensory substitution system for people with a vestibular dysfunction (Wall 3rd, Weinberg, Schmidt & Krebs, 2001). The same concept is applied in TOAST: a localised vibration on a matrix display of vibrators on the astronaut's torso indicates 'down' in any chosen reference frame as if it was an artificial gravity vector. Because the tap-on-the-shoulder is considered an intuitive way to present spatial information, the display may become a 'sixth sense' (the vestibular system is sometimes also called the sixth sense). In this case, with sixth sense we mean that the astronaut uses the information without thinking or requiring cognitive resources, or without even being aware that the information is there. Interestingly, the role of tactile information on the sole of the feet has already been shown in spaceflight. During visual roll stimulation in spaceflight, a bungee cord apparatus that pulled the astronaut against the spacecraft deck generated tactile stimulation. It was found that bungee loading could attenuate the visually induced sense of self-motion in roll and induce tilt in space flight (The National Academy of Sciences, 1988). It has also been suggested to use localised vibrations on the astronaut's torso to display orientation information (Rochlis & Newman, 2000).

Orientation Awareness

Although TOAST could in principle positively affect performance and well-being in many weightlessness situations, the present state of technology does not allow yet to build a wearable version that does not interfere with the normal duties of an astronaut and that uses an acceptable amount of resources. We therefore expect that the first application areas of such a support tool will be challenging, but relatively rare situations such as Extra Vehicular Activity (EVA), emergency evacuations, and vehicle control during docking. However, the present experiment will test the basic assumptions underlying TOAST in a controlled experiment. In principle, TOAST can:

- enlarge the astronaut's awareness of his orientation;
- support the astronaut in maintaining a desired orientation (more specifically, it will prevent small orientation drifts which might even be below the detection threshold of the vestibular system);
- enable the astronaut to reach a specific orientation faster and with a higher accuracy, and;
- positively affect the general well-being of the astronaut, and prevent the potentially uncomfortable situation when the astronaut perceives the discrepancy between actual and expected orientation (Raj, Kass, Perry, 2000).

To investigate the effects of TOAST on the astronaut's performance, a set of experimental tasks was designed. The set consisted of five tasks of which two (called

[1] The following short names for the experiment have been used: JERKIN and VEST during the preparations and SUIT and TOAST during the execution and dissemination of the experiment. SUIT is the name under which the experiment will be stored in the ESA archives.

'mother Earth' and 'straight & level') were focussed on performance evaluation, two (called 'rotation illusion' and 'rotation adaptation') were of scientific interest, and one (called 'sensation check') was of practical interest. The tasks and specific hypotheses are described in the next section.

Mother Earth task

In this task, the astronaut had to indicate his orientation after being rotated in his roll plane with his eyes closed, like being the hour hand of a clock. There were always ten subsequent trials without being brought back to a known orientation or receiving feedback on performance. The task was done with and without the support of TOAST. The two objectives of this task were a) to measure the effect of TOAST on orientation awareness (we expected improved performance with TOAST), and b) to investigate path integration. Although the absolute orientation awareness of the astronaut will be reduced because of the lack of a gravity vector (i.e., effectively disabling the gravity function of the otoliths), the semi-circular canals still provide information on the amount of rotation. By integrating the consecutive rotations, the astronaut might be able to 'calculate' his orientation. More specific: without the support tool, the absolute error will accumulate over the ten repetitions. Bles (1981) already showed the role of the somatosensory system (referring to receptors in the skin, muscles and joints) in providing information about rotation of the body. It is not clear what the role of the ideotropic vector might be in this task. The tendency to take one's own body axis as up may lead to a bias in the answers towards 12 'o clock. This bias may be present in both conditions but may also become stronger in the absence of other cues.

Straight and level

In this second task focussed on performance, we were interested in the multimodal tactile-visual integration or competition of orientation information. . The astronaut was brought passively in a random orientation with closed eyes and TOAST off. We measured subsequently how fast and accurate the astronaut could determine his orientation after he had opened his eyes and TOAST was switched on, apart or in combination. Because the visual modality is dominant during the first stay in microgravity, we did not have an explicit hypothesis about the comparison between tactile only and visual only. There may be an effect of adaptation, because of the tendency of visual cues becoming less dominant over time. We expected the multimodal condition to result in the best performance because there are no indications that the integration of congruent tactile and visual orientation information is accompanied by costs in time or accuracy (Van Erp & Verschoor, 2004). This may only be true however, as long as the tactile and visual information are congruent.

Rotation illusion

In this task, the astronaut was brought into a slow pitch rotation and indicated whether he perceived that he was rotating or that the ISS was rotating. This task was not focussed on performance. The goal was to determine the effect of tactile stimulation on the shift from a stable ISS (i.e., visual cues are dominant) towards a stable self (i.e., the ideotropic vector is dominant), a state that is sometimes observed during adaptation to weightlessness. During such a rotation, the vestibular semicircular canals detect self-motion at the onset of the rotation, a sensation that subsequently should be sustained by the visual pitch motion stimulus (match with a rotating astronaut). If the system still expects a rotating gravity vector as otolith signal, the interpretation would be a rotating ISS. The ideotropic vector also indicates towards a stable astronaut). There has not been any systematic data recording of this phenomenon in the past. Anecdotal evidence

(Clement, 2004; Wood, 2004) indicates that during relatively short (Shuttle) flights about 25% of the astronauts are purely z-axis oriented (i.e., have a dominant ideotropic vector) while 75% is either visually oriented or are alternately z-axis and visually-oriented (the latter may be related to time in orbit). There is also anecdotal evidence that some astronauts perceive themselves to be stable during small translations. For example, they have the feeling of pushing the station or the shuttle away, while pushing themselves away from the floor or the walls.
This rotation illusion task was performed with eyes open and with TOAST either on or off. We originally hypothesised that the illusion of a rotating ISS would occur during adaptation to microgravity, but only in the condition without TOAST, since TOASTwas designed to inform the astronaut that he was rotating.

Rotation adaptation
In this task we measured the adaptation of the vestibular system (i.e., the semi-circular canals) in micro-gravity to an angular velocity step response and the effect of the tactile support on this response and adaptation. For this purpose the astronaut was brought into a constant rotation and indicated the moment the rotation sensation died out. The task was performed with closed eyes and with TOAST either on or off. We hypothesised that the response time would be larger with the support tool on and increasing over flight time. This task also touches upon the relevant issue of TOAST acting as a sixth sense. Advocates of comparable displays and applications are inclined to postulate that these displays are intuitive and that the presented information will be processed by the user without any cognitive effort and without requiring conscious perception of the information. If such displays are capable of intervening with low level processes such as the adaptation time of the semi-circular canals, this may be an indication that they truly act as a sixth sense.

Sensation check
In this task, the astronaut had to react as fast as possible to individual tactors activated in a random pattern. Previous research has shown that tactile perception may be degraded in altered G environments. For example Tan and colleagues found negative effects of 0 G on detection, perceived intensity, and pattern perception, but Van Veen and Van Erp showed that detection was not affected under high G loads (Tan, Lim & Traylor, 2000; Traylor & Tan, 2002; Van Veen & Van Erp, 2001).

2 Method

The experiment was performed by a single subject, a male ESA astronaut, during his 10-day mission to the ISS as a visiting scientist. During the experiment, the subject was assisted by a second crewmember who moved the subject, read out the questionnaire and cared after the safety of the subject. The experiment was approved by the human subjects committee of TNO Human Factors and the ESA Medical Board. The subject agreed with and signed an informed consent before the training and the experiment. All equipment involved in the training or the experiment was approved and/or certified by ESA and/or Russian safety officials. The experiment was done in the node, a specific module of the ISS, also depicted in Figure 8.

2.1 Specific equipment

For the experiment, two versions of the support tool were built: one for the training sessions and the debriefing (TrM, Training Model) and one for the experiment (FM, Flight Model). Both versions were custom made by Dutch Space, Leiden, The Netherlands and are not described in detail here (please see Appendix 1 for the ESA documents of the experiment, its crew procedures, hardware, etc.). All technical and medical aspects of the hardware were checked, judged, and approved by ESA, and partly by NASA and the Russian Space Agency. Important hardware specifications were the following: the drift in the gyroscopes was less than 5° per half hour (they were calibrated every 30 minutes), the delay in the system was less than 50 ms, the update rate was better than 30 Hz. Both models were practically equal but only the FM was flight qualified. The main parts of the support tool were:

- 56 vibrating elements called tactors. The tactors were based on vibrating motors as applied in mobile phones and pagers and vibrated at 160 Hz. The motors were housed in small aluminium boxes (see Figure 1) with a circular contact area. The response to a 50 ms pulse is given in Figure 2.
- A multi-layered Nomex ® garment. The garment contained the tactors in a semi matrix layout (see below for details), and six pouches for two battery packs, three gyroscopes and a voicerecorder. The garment was custom made to fit the astronaut but was also adjustable to provide the tight fit needed to ensure contact between the tactors and the astronaut's body. The tactors were placed in between the inner two layers, the cables and electronics in between the outer two layers.
- A cotton T-shirt, worn under the garment.
- Two battery packs (fused), each consisting of five Duracell procell type AA batteries. The battery packs were used for one session and were disposed of afterwards.
- Three gyroscopes in orthogonal position.
- A control unit worn on either the left or the right lower arm, containing micro electronics, the astronaut-tool-interface (ATI) and two Compact Flash (CF) card slots. The ATI consisted of several pushbuttons, a four-line LCD and a speaker to provide auditory feedback. The speaker was also used to synchronise the voice recorders with the data stored on the CF cards.
- An astronaut voice recorder that recorded the responses and remarks of the astronaut during the experiment.
- An assistant voice recorder that recorded the instructions and remarks of the assisting crew member during the experiment.
- Two CF cards that stored TOAST data, amongst others the status of the tool, the active tactor, the gyro signals, and several calibration settings. The cards were used

for one session. One was stored as back-up, one was returned with the astronaut after the mission.

- A Nomex ® blindfold.
- Ear mufflers that were part of the standard outfit of ESA astronauts.

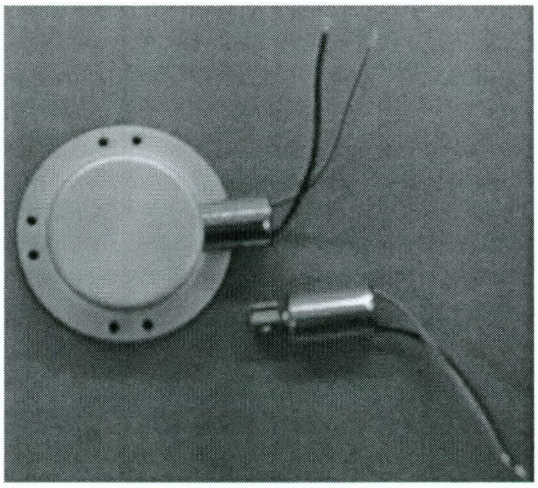

Figure 1 The housing and a vibrator motor (a motor protrudes from the housing for clarity). After installing the motor the housing is closed and sealed.

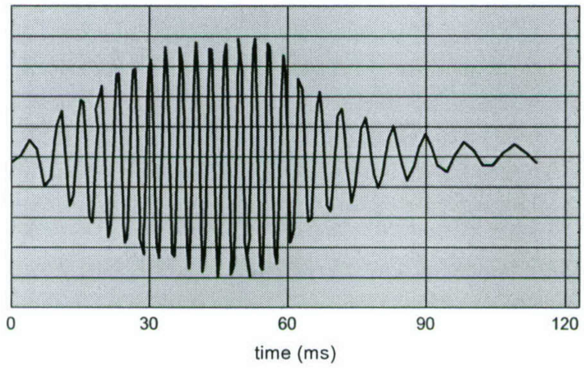

Figure 2 Response characteristic of the tactor for a 50 ms burst. The amplitude scale here is arbitrary since amplitude is strongly dependent on the pressure with which the tactors is pressed to the astronaut's skin. The vibration frequency is 160 Hz.

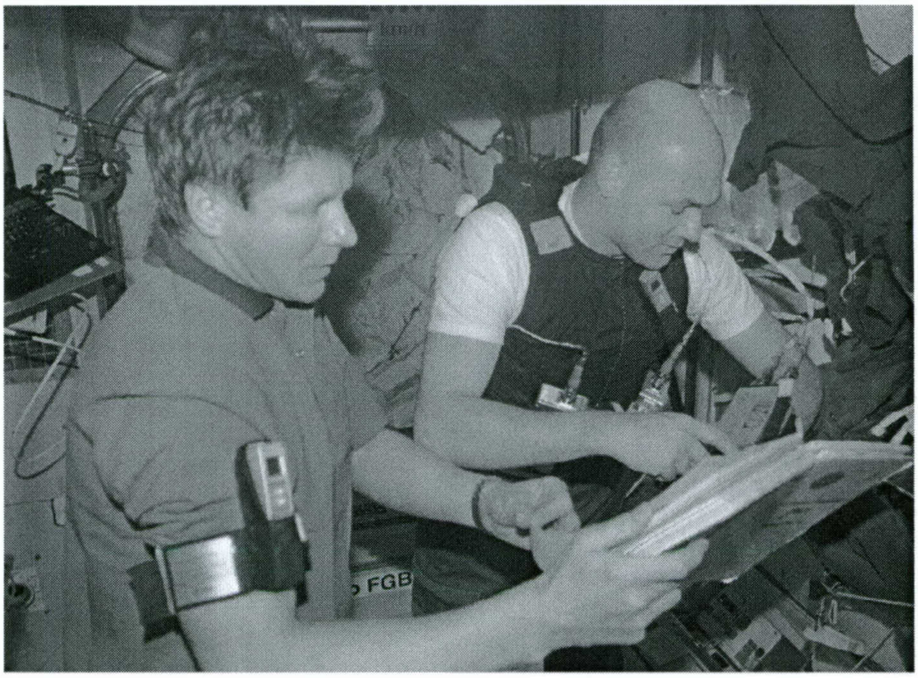

Figure 3 The assistant (left) wears the voice recorder on his right upper arm (photo NASA/ESA).

Figure 4 The astronaut wearing the equipment, including the vest with the tactors, the voicerecorder (high on his chest), two batterypacks and the control unit on his left lower arm (photo ESA/NASA).

2.2 Placement of the tactors and control model

The model that calculated the tactor that indicated down (see Figure 5 for the concept), converted the gyroscope signals in two angles (heading and pitch) that had the astronaut's body as (fixed) reference frame. Figure 6a gives a schematic overview of the placement of the tactors in this same reference frame. In Figure 6b, the locations of the tactors are depicted by the stickers on the outside of the TrM. Each of the 56 tactors covered a specific segment and was activated when the calculated heading and pitch angles were within it's segment. This basic model was extended with the following two features: a) for a pitch above 80° (i.e., an upside-down orientation), four of the eight tactors in the upper ring were activated simultaneously; b) the tactors in the lower ring could be activated in different rhythms as function of the pitch angle. The standard rhythm for all tactors was 100 ms on – 200 ms off. For the lower ring, the following rhythms were used: pitch below -80° (i.e., almost upright): tactors off, pitch between -80° and -75°: 40 ms on – 40 ms off, pitch between -75° and -70°: 60 ms on – 60 ms off, pitch between -70° and -65°: 80 ms on – 80 ms off, pitch between -65° and -60°: 100 ms on – 100 ms off.

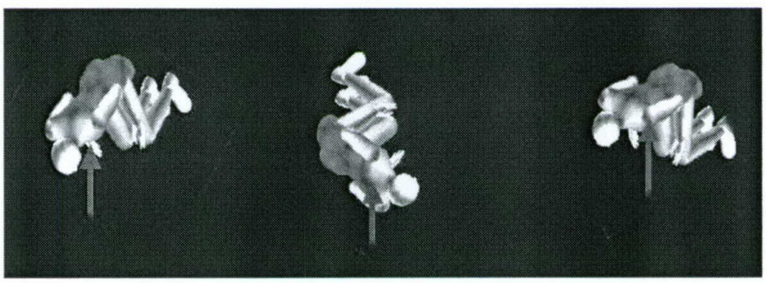

Figure 5 The concept of the artificial gravity vector. Ones the astronaut has chosen a reference frame, the direction of the gravity vector in this reference frame is indicated by a localised vibration on the tactile display.

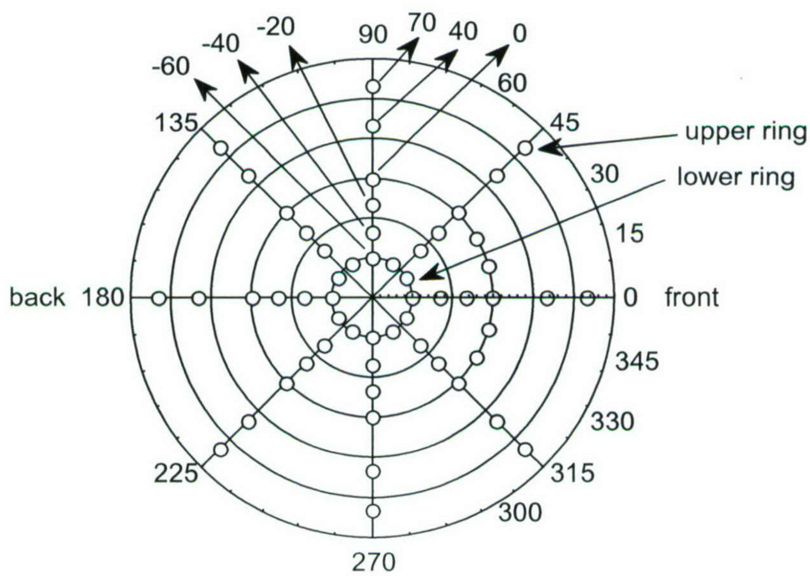

Figure 6 Placement of the 56 tactors, a) according to the model expressed in heading and pitch angles with the astronaut's body as reference frame. A heading of 0° is the midsagittal plane, the circles represent the different rings around the torso, with -60° representing the ring just above the waistbelt and 70° the ring on the collar. And b) indicated by stickers outside the front and back side of the training model.

2.3 Task set

The task set consisted of the following tasks, the specific rationale and hypotheses of each task are given in the Introduction. The task set was completed in a fixed order of tasks and conditions and on four different days during the mission (see procedures below).

Task name: sensation check
Short protocol: during the start-up and testing of the equipment, all tactors were activated one by one in a random order. The task of the astronaut was to respond as fast as possible to each tactor by pushing a button on the ATI.
Score: reaction time.
Timing/repetitions: performed during start-up at the beginning of each session.
Sessions: on flight day (FD) 4, 5, 8 and 9.

Task name: mother Earth
Short protocol: starting from a standard reference orientation, the astronaut closed his eyes and was positioned in different orientations in his roll plane by a colleague (like the hour hand of a clock), see Figures 7 and 8.
Score: indicate (verbally in terms of clock hours) the orientation with respect to the standard orientation.
Conditions (2): with and without TOAST.
Timing / repetitions: 10 different orientations (without returning to the standard orientation) per condition per session.
Sessions: on FD 4, 5, 8 and 9.

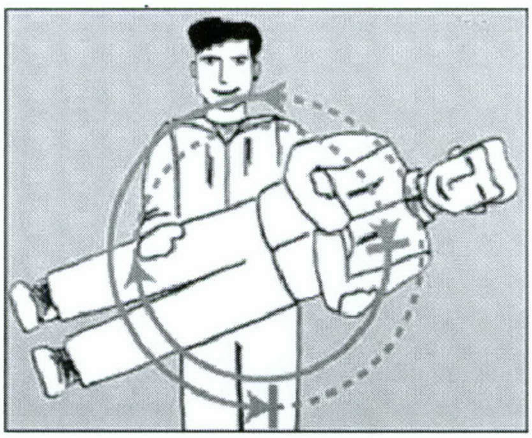

Figure 7 Illustration taken from the crew procedures for the Mother Earth task.

Figure 8 Picture taken during the experiment while performing the Mother Earth task. The astronaut wears a blindfold (photo NASA/ESA).

Task name: straight and level

Short protocol: the astronaut (with eyes closed and TOAST switched off) was brought into a random orientation from the reference orientation by a colleague. After a start signal, the astronaut opened his eyes and/or switched TOAST on (depending on the condition) and reported where down was using a verbal coding (8 sectors based on (head or feet) × (front or back) × (right or left), e.g., head, front, left). For each new trial, the subject started from the standard orientation.

Score: response time and proportion correct.

Conditions (3): visual only, TOAST only, and visual + TOAST.

Timing / repetitions: 3 repetitions per condition per session.

Sessions: on FD 4, 5 and 8.

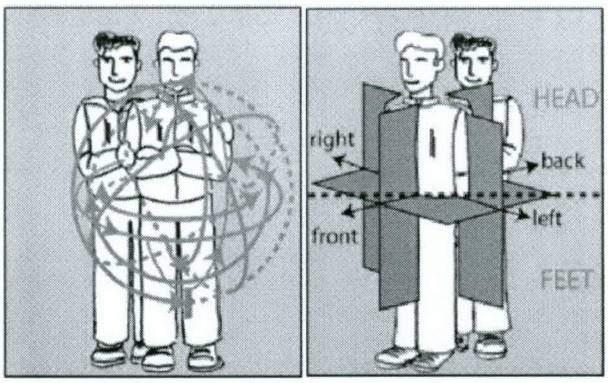

Figure 9 Picture taken from the crew procedures for the straight & level task.

Task name: rotation illusion
Short protocol: a colleague brought the astronaut into a slow rotation (in the order of 45 °/s) in the pitch plane of the astronaut (like a somersault).
Score: are you (astronaut) rotating or is the ISS rotating?
Conditions (2): with and without TOAST.
Timing / repetitions: 1 repetition per condition per session
Sessions: on FD 4, 5, 8 and 9.

Task name: rotation adaptation
Short protocol: the astronaut had his eyes closed and was brought into a slow constant rotation by a colleague (order of 45-90 °/s).
Score: astronaut indicated the moment that the sensation of rotation died out.
Conditions (2): with and without TOAST.
Timing / repetitions: 6 repetitions per condition per session (each cardinal axis clockwise and counter clockwise).
Sessions: on FD 4, 5, and 8.

2.4 Data gathering and processing

During and after the experiment, the following data were gathered:
- Hardware data logged on the CF cards, including gyroscope data, condition, and calculated tactor. These data were stored in all conditions, also in the conditions when TOAST was off. Based on these data, objective performance measures (such as reaction times) were calculated after return.
- Voice recorder data, including task performance data (e.g., the perceived orientation as hours of the clock in the mother Earth task) and questionnaire data. The questionnaire contained the following questions for the sensation check:
  1. Do the vibrators feel different than during the training on Earth, and if yes: can you describe the difference?
  2. Are the vibrators more intense or less intense than during the training?
  3. Are the vibrators easier or harder to localise than during the training?

  For the other tasks, the following questions were asked:
  1. How difficult was this task on a scale of 1 (no problem) to 5 (hardly doable)? Asked after each condition.
  2. Did you use a specific strategy in this task? Asked after each condition.
  3. Did TOAST support you in this task? Asked after the last condition of each task.

4 Would you use TOAST voluntarily for these kind of tasks? Asked after the last condition of each task.

Also, after a complete session, open questions about comfort, applications, improvement, etc. were asked. Both subject and assistant were encouraged to make remarks and speak out observations during the experiment.

- After return, two debriefings were organised in which the astronaut reflected on the experiment and the results.

2.5 Basic Data Collection and Training

A total of four sessions were held within six months prior to the mission. They were all done with the TrM. The first two were done at TNO Human Factors and were focussed on optimising the equipment (e.g., the fit of the garment) and familiarisation with TOAST. Figure 10 shows an example of the familiarisation using a rotating chair. The last two were done at Star City, Moscow, Russia, and were focussed on the procedures of performing the task set and operating the equipment, and the interaction between astronaut and assisting colleague. During these sessions, baseline data for the sensation check were gathered. The final crew procedures were made by the Russian Space Agency, based on input provided by TNO Human Factors. During the first session in the ISS, the crew used the full crew procedures for the experiment, in the following sessions they used the short version of the procedures (so-called Q-cards).

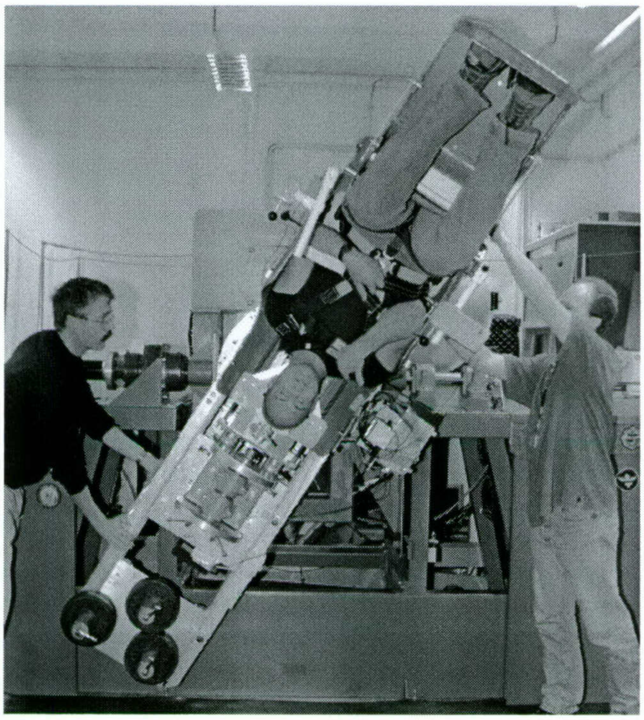

Figure 10 Picture taken during one of the familiarisation sessions in the 3D-rotating chair at TNO Human Factors. The astronaut experiences TOAST and indicates down with his right hand.

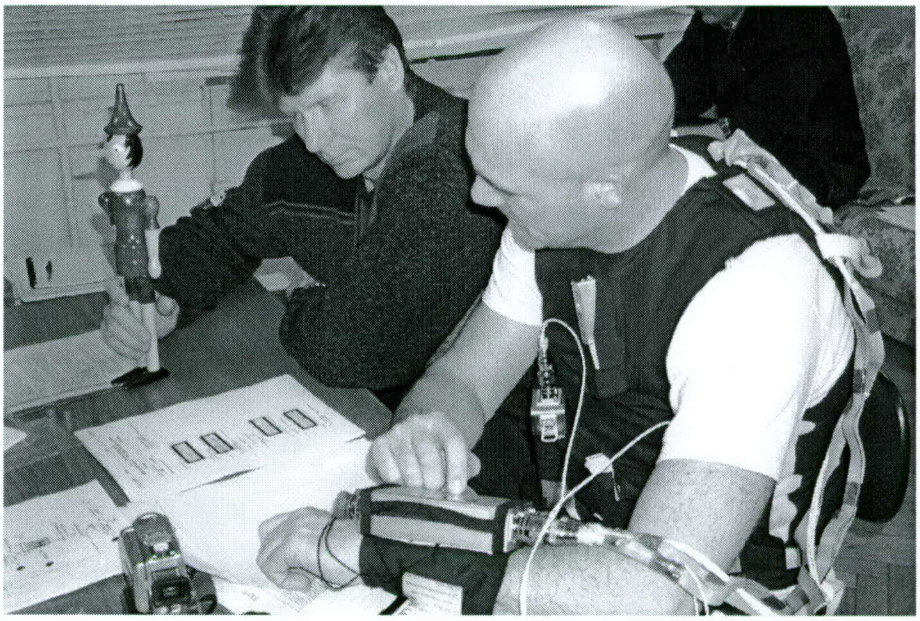

Figure 11 Astronaut and assistant were trained together in the crew procedures. They also trained using a wooden doll.

2.6 Procedures and test schedule

The complete crew procedures were printed on 57 pages. An overview of the procedures that are relevant from an experimental point of view is presented below. Each session started with collecting and preparing the relevant equipment. This included two fresh battery packs and two fresh CF cards for each session. Before starting the experiment, the following steps were taken:

- Adjusting the intensity level of the tactors (level 1-6). This was done while a random pattern of tactors was played on TOAST. The setting was stored on the CF cards.
- The sensation check. During this procedure, the control unit presented each of the 56 tactors once and in random sequence. The task of the astronaut was a simple reaction time task: upon detection, he pushed a button on the control unit. There was a random interval between 500 and 1500 ms between the pushing of the button and the presentation of the next tactor in the sequence. The reaction time for each tactor was stored.
- Calibration of the gyroscopes. During this procedure, the astronaut had to be motionless for 20 seconds during which the rotation of the ISS was measured to be able to compensate for the rotation of the station, which is in the order of 200° per hour. During this procedure, an auditory beep was presented each second, to indicate the process progress and to synchronise the main unit with the two voice recorders.
- Setting the standard orientation. In this step, the astronaut took the orientation that he wanted to be the standard (i.e., he stood upright in his chosen reference frame) and locked this orientation.

The gyroscope calibration was repeated at least once every 30 minutes; setting the standard orientation could be done at any moment, usually at the beginning of a new task or condition.

The experiment was done in the following, fixed order:

1 Sensation check;
2 Rotation illusion with TOAST off;
3 Mother Earth with TOAST off;
4 Mother Earth with TOAST on;
5 Rotation illusion with TOAST off;
6 Rotation illusion with TOAST on;
7 Straight and level with eyes open nd with TOAST off;
8 Straight and level with eyes closed and with TOAST on;
9 Straight and level with eyes open and with TOAST on;
10 Rotation illusion with TOAST on.

Sessions were performed on four different days as depicted in Table 1 below. Due to time restrictions, the fourth session could not be completed.

Table 1 Overview of the timing of the four sessions and the tasks performed.

Session	Flight day	Full day in ISS	Task set	Measuring time (min)
1	4	1	Full, step 1-10	50
2	5	2	Full, step 1-10	40
3	8	5	Full, step 1-10	40
4	9	6	Restricted, step 1-6	20

3 Results and discussion

After returning to Earth, the CF cards and voicerecorder files were time matched to be able to identify the relevant sections on the CF cards over which the objective performance measures had to be calculated. Since the hypotheses and data varied widely per task, results and discussion are integrated for each task separately. The ANOVAs and post hoc analyses used an α level of .05; the significant effects in the figures are indicated by * for $p < .05$ or ** for $p < .01$.

3.1 Mother Earth

The performance measure in the Mother Earth task was the absolute error in hours of the clock since the response was given in hours of the clock. The task was done in two conditions: with TOAST on and with TOAST off. The absolute error was significantly lower with TOAST on ($p < .01$). The absolute error with TOAST off was 2 hours and 50 minutes, close to the expected error when guessing (3 hours). With TOAST on, the error was reduced to 1 hour and 16 minutes. This value is in the same range as the resolution of TOAST (with eleven tactors for 12 hours, the mean resolution per tactor is 1 hour and 5 minutes) and the resolution of the measuring device (the verbal response was given in hours). TOAST also reduced the subjective difficulty score ($p < .01$) from 5 (almost undoable) to 3 (moderately difficult). These results indicate that TOAST is a powerful support tool to orient oneself in situations in which information from other sensory systems is degraded (the otoliths and eyes in this case). The semicircular canals, however, could in theory provide useful information about the amount of rotation. By integrating angular velocity data over time, the angular displacement can be judged, although observers are not very good at this (Guedry, 1974, p. 44-45). However, in the condition without TOAST, already the second out of the ten repetitions had an absolute error at the guessing level (3 hours) (mean absolute error for the first repetition was 1.5 hour). Also, there were no indications in the subjective remarks on the question about the strategy that the astronaut used this option, also not when explicitly suggested during the debriefings.

The performance at chance level might also be related to the fact that the subject afterwards reported that translating his notion of orientation into the hour hand of a clock was far more difficult than it appeared during the training sessions on Earth. It is a common finding that the cognitive abilities suffer from a microgravity environment. This may also have affected the performance in the TOAST only condition.

3.2 Straight and level

In the straight and level task, two objective performance measures were calculated: the RT (defined as the time between the command of the assistant and the start of the astronaut's answer) and the proportion correct. This task was done in three conditions: eyes open and TOAST off, eyes closed and TOAST on, eyes open and TOAST on. Analyses of variance revealed a significant effect of condition on both the RT ($p < .01$) and the proportion correct ($p < .05$). The means and the results of post-hoc Tukey tests are given in Figures 12 and 13. There was also a significant effect on the subjective difficulty score ($p < .02$). The means are presented in Figure 14.

On the question "have you used a specific strategy to complete this task?", a changing attitude over the sessions can be seen. This task was done during the first three sessions. Relevant quotes from the astronaut's responses were the following: session 1: "*the*

tactors help very much to verify what you see"; session 2: "*easy to get a global idea, verified with my eyes*"; session 3: "*I didn't look, only the vest*". This indicates a change from visual dominance in the first session to tactile dominance in the third.
The results show that TOAST has a positive effect both on performance and on task difficulty, and not in challenging situations only. The task is performed much faster with TOAST on, although in the condition with TOAST off, the astronaut still has full visual information. TOAST not only results in faster reactions but also in better scores. The score in the condition without TOAST is above chance (.125 in this case) but still incorrect in two out of three cases. This indicates that it is either very difficult to orient oneself based on the available (visual) information (see Fig. 8, which shows that visual cues of up and down at the site where the experiment took place are mainly provided by text messages and equipment), or that it takes even more time than the 7 s under the present instruction to answer as fast and as accurate as possible. Although the difference is not significant, the score in the condition with eyes and TOAST is only half that in the condition with eyes closed and TOAST. This may indicate a response competition in which the astronaut relied on misinterpreted visual information. The used strategy as mentioned in the questionnaire might be an indication that he realises this and starts to use TOAST only in the multimodal condition and ignores the (unreliable) visual information. The data are in accordance with the common observation that visual cues become less dominant during adaptation to microgravity.

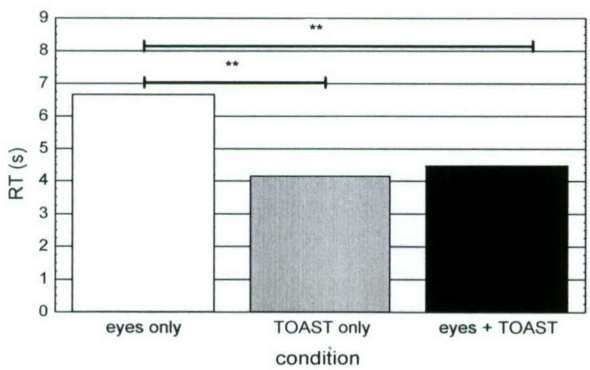

Figure 12 Reaction time in the straight & level task as function of the sensory condition. Performing the task without TOAST is significantly slower.

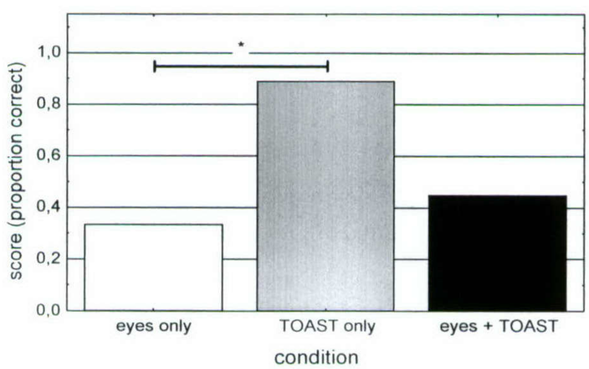

Figure 13 Task performance in the straight & level task as function of the sensory condition. Task performance with TOAST only is significantly better than without TOAST.

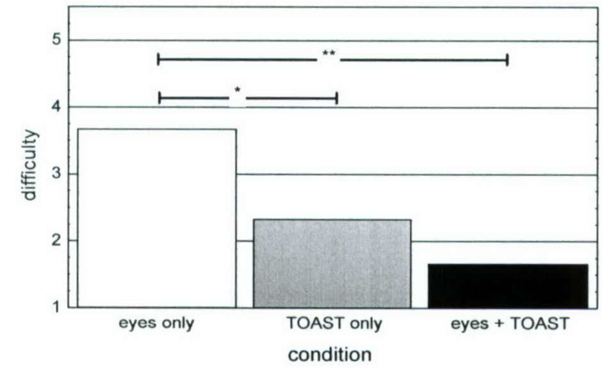

Figure 14 The subjective difficulty score in the straight & level task as function of sensory condition. Without TOAST, the task is judged significantly more difficult.

What might be interesting is to look at the scores per dimension. Table 2 presents the proportion wrong answers per condition and dimension.

Table 2 Proportion wrong answers in the straight and level task as function of response dimension and condition.

	Head / feet	Front / back	Left / right	mean
Eyes only	.44	.33	.22	.33
TOAST only	.14	.00	.00	.05
Eyes and TOAST	.63	.00	.25	.29

Clearly, most wrong answers are in the head / feet dimension. Table 3 presents the confusion matrix for this dimension.

Table 3 Confusion matrix for the answers on the head/feet response dimension in the straight and level task pooled over all conditions.

	Answer head down	Answer feet down
Position head down	6	1
Position feet down	9	2

Table 3 indicates that the astronaut had either a bias of calling that his head was down, or he doesn't recognise his orientation and therefore presumes that he is not in the same orientation he was at the start of the trial. The asymmetrical layout of the node (with a floor and a ceiling and four corridors in between, see Fig. 8) may also have played a role, although it is not a priori clear how exactly.

3.3 Rotation illusion

For the rotation illusion, there was no objective performance or difficulty defined. Table 2 gives the astronaut's answers. In session 4, the task was done with TOAST off only.

enlarge the adaptation time of the vestibular system is important with respect to some of the assumptions or claims of TOAST and TOAST related devices. More generally, tactile torso displays are claimed to be intuitive: there is no cognition or even consciousness required to process spatial information, like we reflexively turn around when somebody taps us on the shoulder. If this claim is substantiated, it may support a derived claim, namely that such displays have beneficial effects on (mental) workload. This is important, because then these displays may improve safety, comfort and performance without placing any burden on the (restricted) cognitive and perceptual resources of the user: a real panacea for overloaded operators. Indications for these effects are present in the remark the astronaut made during the debriefing (without being aware of the above mentioned issues): "*In daily life, you don't pay attention to the vibration anymore; you can feel them but they didn't get into my system*". Although he interpreted this as a negative aspect, it may also be a sign that the tactile information is becoming a sixth sense that processes information without knowing it, like we process visual and vestibular information without being constantly aware what these senses tell us about our orientation. Again, these are indications only, and no firm conclusion can be drawn on the basis of the present data. What is important, however, is that the question whether the tactile information may affect the adaptation time of the vestibular system is still open. When this is the case, it is hard to tell whether this influence is cognitively or not. On the other hand, if it really would be a cognitive effect, the astronaut would never report that the rotation stopped unless he was grabbed and stopped by the assistant, and Bles (1981, p. 59) argued that vestibular and somatosensory signals converge at the vestibular nuclei, so at a subcortical level.

3.5 Sensation check

In the sensation check, we used only one dependent variable: reaction time to the tactors. There were also several questions in the questionnaire focussed on the perception of the tactors. The sensation check is also the only task with a baseline. In total, the astronaut did nine sessions: two during the training in Star City (3 and 1 month before the mission), five in microgravity during session 1, 1, 2, 3, and 4, and two during the second debrief at ESA/ESTEC in Noordwijk, The Netherlands (2.5 months after the mission). Figure 15 depicts the mean RT as function of session. An analysis of variance revealed that the RT in microgravity is significantly faster than in 1G ($p < .01$). The mean in microgravity was 683 ms versus 775 ms in 1G. There is no obvious reason for this advantage. On the contrary, the few studies done in a microgravity environment (focussed on intensity and pattern perception in the NASA Reduced Gravity Aircraft: Tan, Lim & Traylor, 2000; Traylor & Tan, 2002) indicate that tactile perception is negatively affected by reduced gravity. However, these studies were done with students as observer who's performance may be largely determined by the for them unknown and possibly stressful experience. What should be noted is that the effect is confounded with the use of the TrM in 1G and the FM in 0G, although they were by design equivalent with respect to tactors, garment, power supply and electronics.
There was also a significant difference between the different tactors ($p < .02$). Although most tactors had a RT between 600 and 800 ms, there were nine tactors that had a RT in microgravity above 800 ms. These are marked in Figure 16. It is also interesting to look closer at the tactors that have a higher RT in microgravity compared to that in 1G, despite the overall performance gain in microgravity. These tactors are marked in Figure 17. These figures indicate that, although the garment was custom made for the astronaut, the fit at the lower and upper rings may be improved. Also, the fit may be degraded in microgravity: despite the general advantage in microgravity, the 15 tactors

that have a larger RT in microgravity as compared to 1G are mainly distributed along the upper and lower ring. The optimised fit for 1G may be less optimal in microgravity due to a different posture and shifts in body fluids.
In the questionnaire, the following three questions were asked:

1 Do the vibrators feel different than during the training on Earth, and if yes: can you describe the difference?
2 Are the vibrators more intense or less intense than during the training?
3 Are the vibrators easier or harder to localise than during the training?

The astronaut said no to all three questions. During the debriefing he also clearly indicated that he experienced no difference between the 0G and 1G situation with respect to the tactile stimuli.

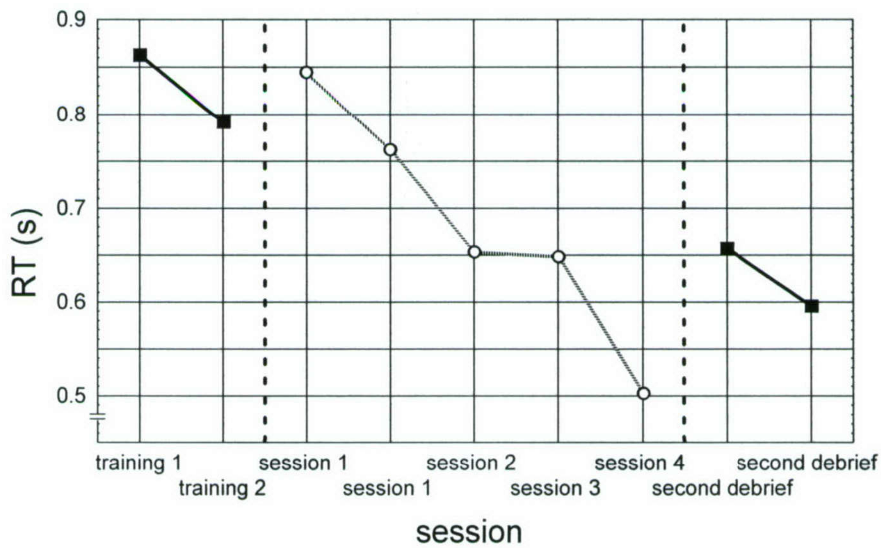

Figure 15 RT to the tactors during the training sessions in Star City, the experiment in the ISS and the second debriefing in Noordwijk. Overall, the reaction times are significantly faster in microgravity than in 1G.

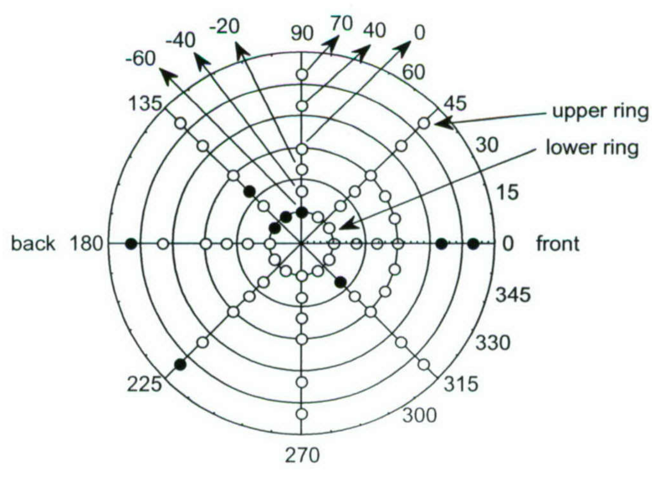

Figure 16 The marked tactors have a mean reaction time above 800 ms.

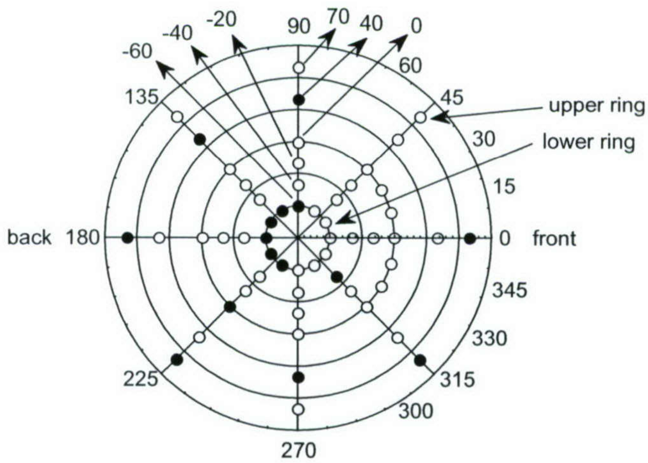

Figure 17 The marked tactors have a slower reaction time in microgravity than in 1G. These tactors seem to be concentrated on the lower and upper rings and on the back of the astronaut, probably due to a less optimal fit of the garment in microgravity.

3.6 General questionnaires and debriefings

Besides the questions about task difficulty and strategy and the feel of the tactors, there were also more general questions in the questionnaires. Due to time restrictions and 'no new facts to tell', the subject did not give an answer in all cases. Below, the verbatim text is presented.

- On the question "Did TOAST support you?", the astronaut answered yes in all tasks and sessions. Quotes include: "*yes, I knew where the ground was*", "*gave me a reality check*", "*I thought so, yes*", "*oh yes, I only used TOAST*".
- On the question "Would you use TOAST voluntarily for these kind of tasks?", there is a changing attitude over the sessions. Quotes session 1 are: "*I could try to see if it helps*", and "*Yes, I think it would help*". Quotes session 2 are: "*only for the task, not for daily life*", "*if you want to know that you're turning, TOAST is useful. Not use it on a daily basis*", and "*it is not reliable enough hanging straight*". And quotes session 3 are: "*only for the task, not for to use it no*", "*I don't think it is needed in the station*", "*if I could not use my eyes it would be useful. But in the station there is no, you know we everything. You don't need to know where the floor is*".
- On the question "*Do you have suggestions for improvements?*", the following was suggested:
  - Session 1:
    - Comfort is OK
    - The tactors are activated when I am in reference position so I don't trust them so much
    - overall judgement: 3-4
  - Session 2:
    - Reliability should be improved
    - The cables are too bulky (stuck everywhere)
  - Session 3:
    - there should be more sensors
    - Overall judgement: say a 3. You know, I don't need it, but it is not that bad. You can wear it, but it is bulky.

During the first debriefing, the results of the questionnaires were confirmed by the astronaut. Other relevant aspects that were mentioned during the first debriefing were:

- (dis)orientation was only a problem during the first days. Visual orientation was difficult after entering in an unfamiliar orientation: "*oh, this is a new module, and why did they put lamps on the ground...*"
- Difficulties with cognitive aspects, e.g. translating orientation to clock time
- In daily life, you don't pay attention to the vibration anymore; you can feel them but they didn't get into my system
- In the initial phase of the experiment I needed more cognition to interpret the signals than later.

During the second debriefing, the results as given above were presented to and afterwards confirmed by the astronaut. He confirmed that TOAST certainly helps but is not needed in nominal (non-challenging) situations. He also indicated that the information must be very reliable or it will be hard to learn to trust them. The reason for this remark was that he experienced troubles with this issue during the first session. Due to unnoticed drifts between the moment of choosing the standard orientation and the moment he switched on TOAST, he received feedback that he was not upright immediately after switching the support on, while he (mistakenly) thought to be still upright. Although this did not happen in later sessions (probably because he was gaining experience on how to stabilise himself), it negatively affected his trust in the system.

4 Conclusions

The Tactile Orientation Awareness Support Tool was designed to improve astronauts' sense of orientation in challenging situations such as Extra Vehicular Activity and emergency evacuations. The present research model was tested in a controlled task set in the ISS. Of the five tasks, two were explicitly focussed on evaluating performance. In the Mother Earth task, where the astronaut is rotated like the hour hand of a clock, the results show that in a situation without proper visual cues TOAST results in an accurate perception of orientation while the task is undoable with information from the vestibular system only. In the straight and level task, we also included conditions with full visual cues. The results show that performance with TOAST is superior to that with visual cues only. There are even strong indications that the availability of both cues degrades performance compared with TOAST only. Apparently, the visual cues are less reliable but more dominant than TOAST in the response competition. This hypothesis is confirmed by the changing strategy the astronaut used to perform the task, which shifts from relying predominantly on visual cues during the first session to using TOAST only and ignoring the visual cues in the third session. Also, in both tasks, the subjective difficulty rating is improved when TOAST is available. With regard to orientation performance, it can be concluded that TOAST improves performance and lowers task difficulty and may be a valuable support tool for astronauts operating in challenging situations.

In the rotation adaptation task, it was investigated whether TOAST could affect the response time of the vestibular sense to a constant rotation. Although the difference in response times with and without TOAST was in the expected direction, the effect did not reach significance. Due to a minimal number of observations, the standardised effect size of sensory condition (and thus the statistical power) was low in this task. The rotation illusion task was designed to reveal the effect of TOAST on the possible shift from visual cues to the ideotropic vector as dominant cue in determining orientation. TOAST was mistakenly hypothesised to provide unambiguous cues indicating the stability of the environment and thus prevent the illusion to occur. The results show that the illusion indeed occurs during the process of adapting to microgravity. The shift occurs on the fifth day in the ISS and is present in the conditions with and without TOAST support.

Finally, possible differences in tactile experience in microgravity and in 1G were investigated. First, the detection time of the tactors was measured, showing better performance in microgravity than on Earth, despite the fact that the fit of the garment seemed to be less optimal in microgravity. Second, the astronaut indicated that there were no differences between 0 and 1G with respect to the feel of the tactors, their localizability, their intensity, or their comfort. Based on these results, it can be concluded that weightlessness does not negatively affect the usability and potential of tactile torso displays.

During the experiment and the debriefings, the astronaut confirmed the potential of TOAST, but also added that it should be extremely reliable and wearable. As expected, the astronaut indicated that TOAST is thought not to have a surplus value during nominal operations but a possible advantage during challenging situations.

Other applications in and beyond the ISS

The main applications of a tactile support tool are foreseen for challenging or dangerous situations such as Extra Vehicular Activity (EVA), emergency evacuations, or working in confined spaces. Especially when besides the vestibular and proprioceptive

information the visual information is degraded, for example because of smoke, in darkness or caused by field restricting goggles or helmets, tactile information may be of eminent importance and may actually be the only reliable source left for the astronaut to find locations, avoid abstacles and prevent disorientation. On Earth, tactile torso displays have already proven their effectiveness for all kinds of users and applications. The recent evidence gathered with tactile torso displays for amongst others pilots and drivers indicates that these displays can result in superior performance over visual displays in vehicle control (Van Erp et al., 2003), navigation tasks (Van Erp & Van Veen, 2004) in counteracting spatial disorientation (Van Erp et al., 2005), and in high workload situations.
For example, during EVA the visual cues are degraded because of the field restricting helmet. A tactile tool could then enhance orientation awareness by indicating the direction of a stable reference point also when this is behind the astronaut (e.g., the centre of the ISS), enhance safety by presenting directional collisions avoidance warnings, and enhance performance by presenting information on how to navigate towards a desired location. All these applications are successfully implemented on Earth. For possible missions on the Moon or Mars, tactile display applications may even be nearly exact copies of the displays developed for comparable tasks on Earth such as navigating in unknown terrain and vehicle control. As on Earth the same positive effects of reduced workload and increased performance are expected.

Although designing a support tool for challenging situations seems most important, the potential of tactile displays is not restricted to these situations. First, the display may support the astronaut's situational awareness during non-challenging situations as well, for instance by indicating the location of objects or other astronauts in the ISS or as collision avoidance warning. Second, a (whole body) tactile display could compensate for the degraded cutaneous stimulation in microgravity. In this case, tactile patterns can be generated that stimulate the whole body which may result in increased comfort for the astronaut, also during periods of rest. Third, tactile displays may serve as a general warning device. An advantage of tactile displays is that a signal will be felt largely independent of the location of the astronaut, or his or her state (even during sleep), and without disturbing other crewmembers. Finally, the sense of touch can play a role in human-human communication. This might be within the station, but also between crewmembers and for example relatives on Earth. A whole body display may enable astronauts on a long mission to give their kids a "virtual hug".

4.1 General conclusion

All in all, the experimental results constitute a successful proof-of-concept. Vibrotactile orientation cues can compensate for the lack of cues from the otoliths (important for astronauts and for, for instance, people with a vestibular dysfunction). The tactile cues can be better than the visual cues that are available in the ISS interior (important for astronauts, but also for, for instance, pilots and divers). These results substantiate the need to further identify areas where tactile orientation cues can potentially be beneficial and optimise them for those applications.

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6 Signature

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A ESA Reference documents for the experiment

Document Title	Document No.
Technical Specification for the Experiment (TS-EX)	DSM-SUI-100
Technical Specification for the Equipment (TS-EQ)	DSM-SUI-200
Logbook of Equipment	DSM-SUI-200PS
Technical Description (TD)	DSM-SUI-201
Operations Manual (OM)	DSM-SUI-202
Acceptance Test Programme (ATP)	DSM-SUI-203
Equipment Incoming Inspection Manual	DSM-SUI-204
Qualification Test Programme	DSM-SUI-205
Qualification Test Reports and Certificate	DSM-SUI-206
Hazard / Safety Analyses	DSM-SUI-207
Safety Assessment Report	DSM-SUI-207-01
List of Non-metallic Materials/Declared Materials List	DSM-SUI-207-02
Specific Certificates (fire safety, toxicity, etc.)	DSM-SUI-207-11
TrM and Crew Training Documentation	DSM-SUI-208
Inputs to Crew Procedures	DSM-SUI-208-01
Control Test Equipment Documentation	DSM-SUI-209
Detailed Electrical Circuit Diagram (DECD)	DSM-SUI-210-01
General Electrical Circuit Diagram (GECD)	DSM-SUI-210-02
Outline Installation Drawings (OID)	DSM-SUI-211
Investigation Requirements Sheet	DSM-SUI-irs
Life Sciences Research Protocol	DSM-SUI-lsrp
Multinational Space Station Human Research Informed Consent	DSM-SUI-msshric

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15. ABSTRACT (MAXIMUM 200 WORDS (1044 BYTE))

Maintaining a good sense of one's orientation in a microgravity environment such as the International Space Station (ISS) is difficult because information from the vestibular and the proprioceptive system is lacking. Especially in challenging situations such as Extra Vehicular Activity and emergency evacuations an orientation support tool may be of critical importance. This study investigates if astronaut's orientation awareness can be improved by providing a vibration on the torso that indicates the direction of 'down'.

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